



# REVIEW OF THE RESULTS OF REACTOR NEUTRINO EXPERIMENTS


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PROSPECTS OF NEUTRINO PHYSICS

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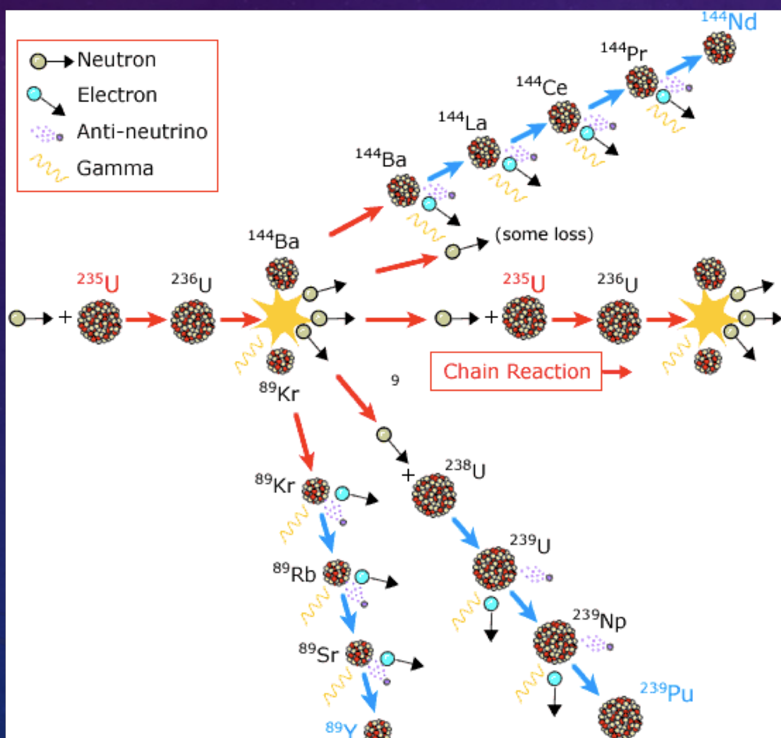
KAVLI IPMU, KASHIWA, JAPAN

# REACTOR NEUTRINOS

- Reactor is a free and rich electron antineutrino source
  - β-decays in a commercial fission reactor core produce$\sim 10^{20}\ \nu/\text{sec}$
  - β-spectra measured at ILL is converted into $\bar{\nu}_e$ yields




Expected neutrino rate:

Target proton number

Detection efficiency

Thermal power

$$N(\bar{\nu}_e) = \frac{N_p \varepsilon}{4\pi L^2} \times \frac{P_{th}}{\langle E_f \rangle} \times \langle \sigma_f \rangle$$

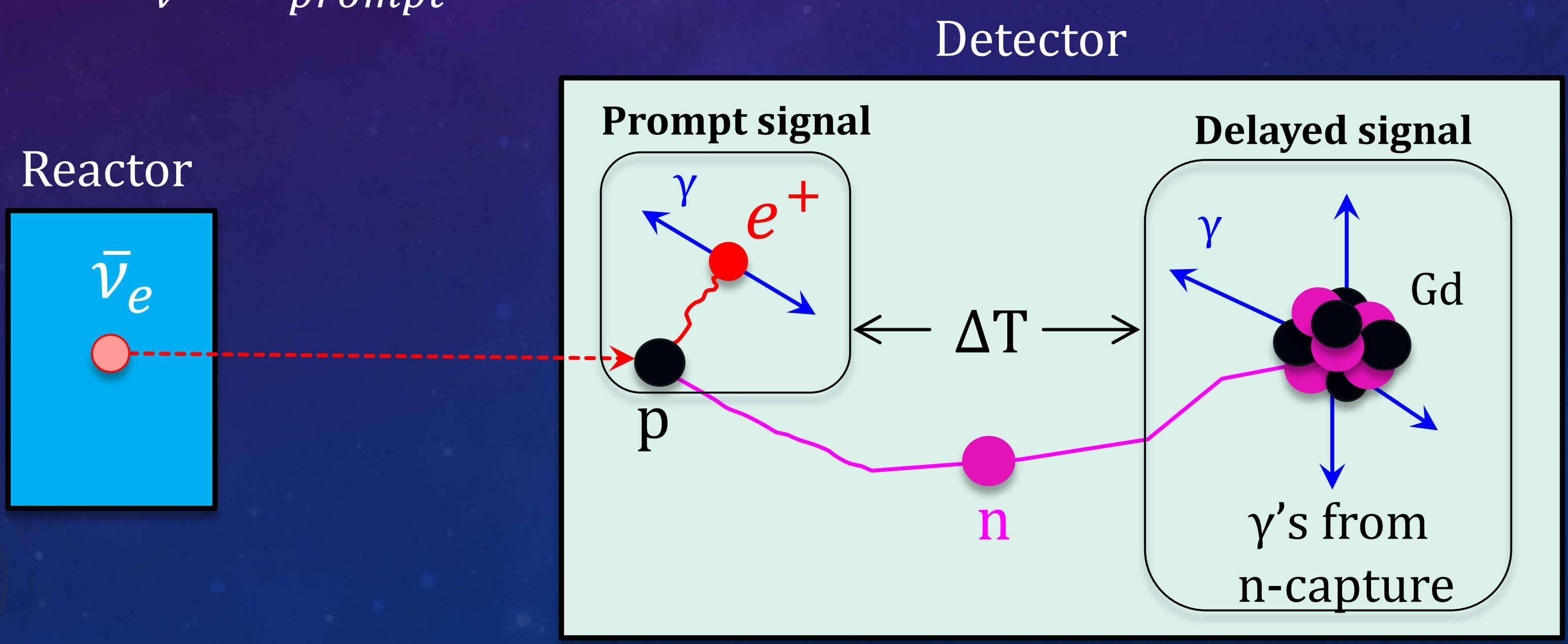
Baseline

Energy per fission

Mean cross-section per fission

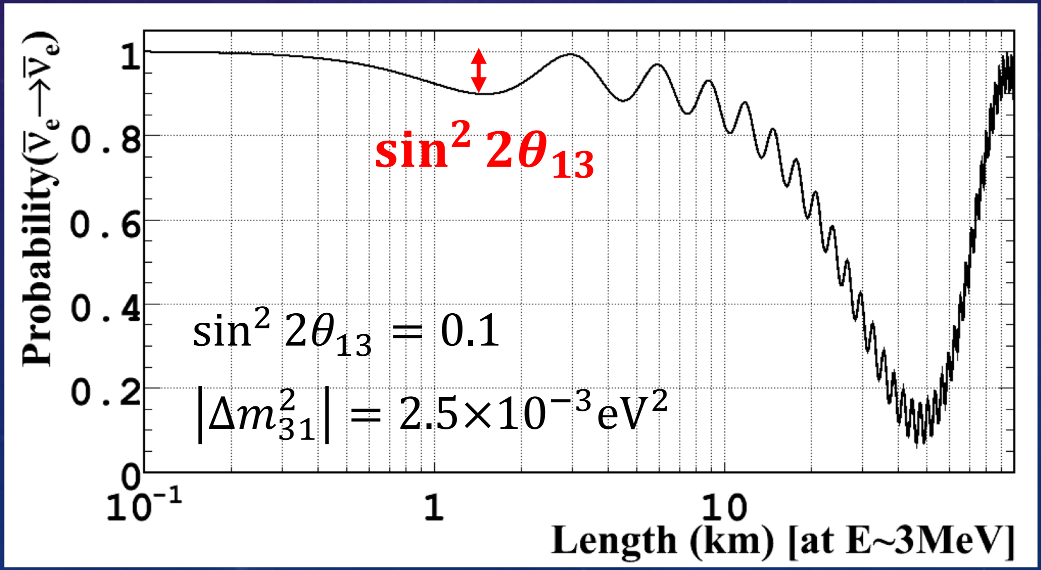
# REACTOR NEUTRINOS

- Reactor $\bar{\nu}_e$ are detected via inverse β-decay (IBD) reaction
  - Delayed coincidence method has been employed to distinguish signals from background since discovery of neutrinos in 1956
  - Gd loaded in recent experiments for n-tag: total 8MeV $\gamma$'s with $\tau \sim 30\mu s$
  - Neutrino energy can be determined from the prompt signal
    - $E_\nu \cong E_{prompt} + 0.78\ \mathrm{MeV}$



# PRECISION MEASUREMENT OF $\theta_{13}$ WITH REACTOR NEUTRINOS

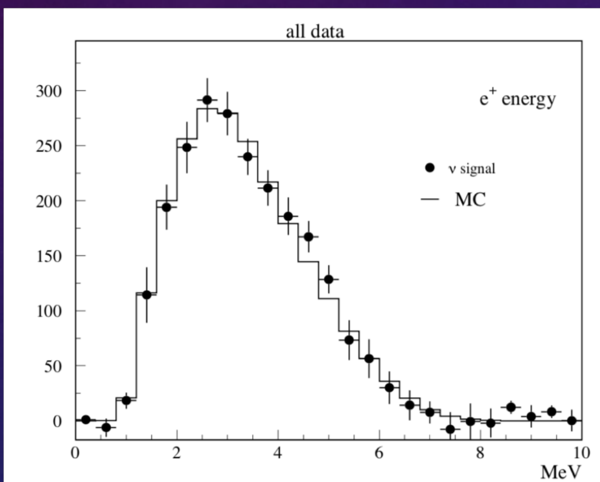
- Simple two flavor oscillation formula is valid at $\sim$1km distance
  - $P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$
  - Direct measurement of $\theta_{13}$ from energy dependent deficit (no parameter degeneracy and matter effects)

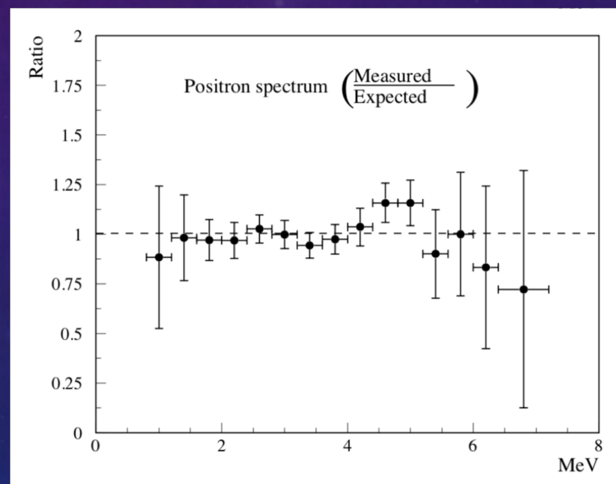


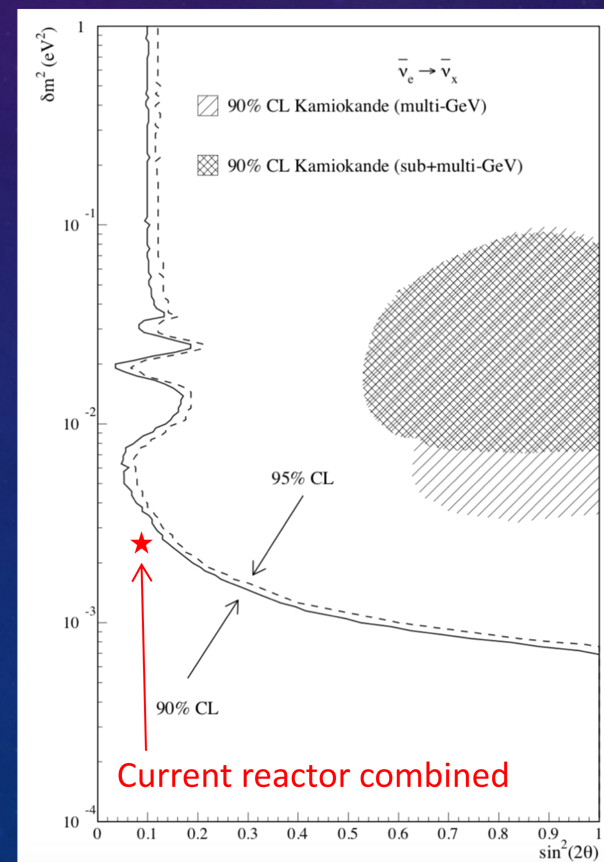
# CHOOZ EXPERIMENT

- CHOOZ experiment measured reactor neutrino spectrum at $L \sim 1\mathrm{km}$
- No significant deficit observed: $R = 1.01 \pm 2.8\%(\mathrm{stat}) \pm 2.7\%(\mathrm{syst})$

*Phys. Lett. B466, 415 (1999)*

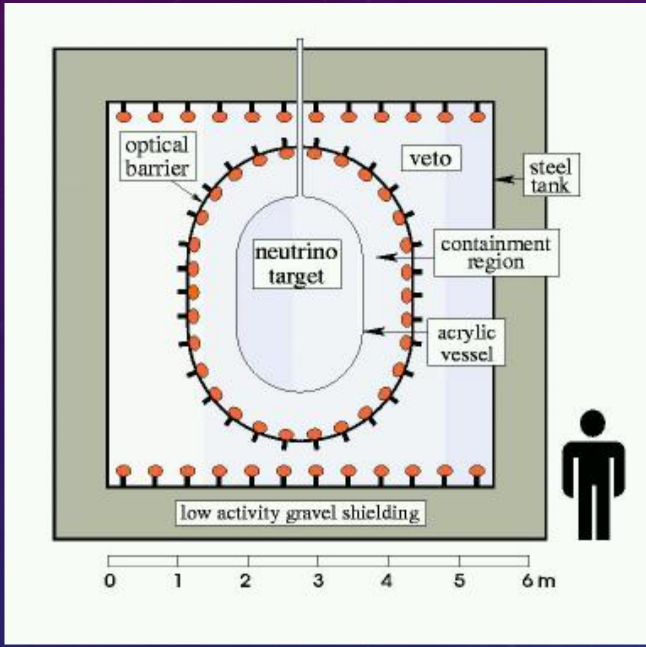


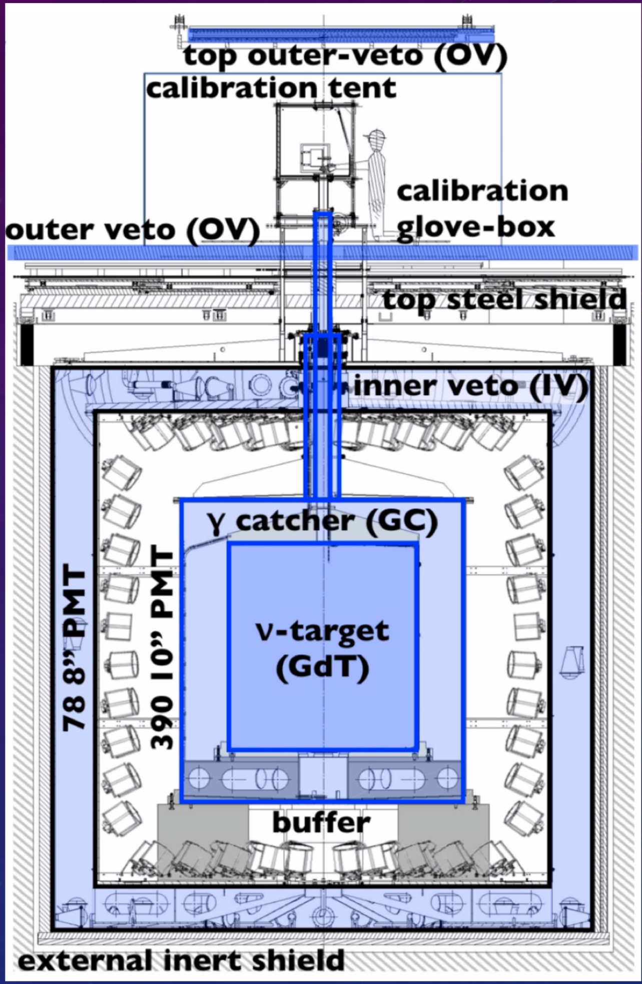




- Measured positron spectrum with reactor-ON after subtraction of reactor-OFF (= background)
- Rate compared with an integrated flux measured at 15m *(Bugey4: Phys. Lett. B338, 383 (1994)*

# IMPROVEMENTS FROM CHOOZ




- 4 layers detector structure with buffer region to suppress background from PMT and surrounding rock → Improve background reduction
- Stable Gd loaded liquid scintillator → Improve statistics with stable operation
- Experimental setup with multi-detectors → Improve systematics (next page)

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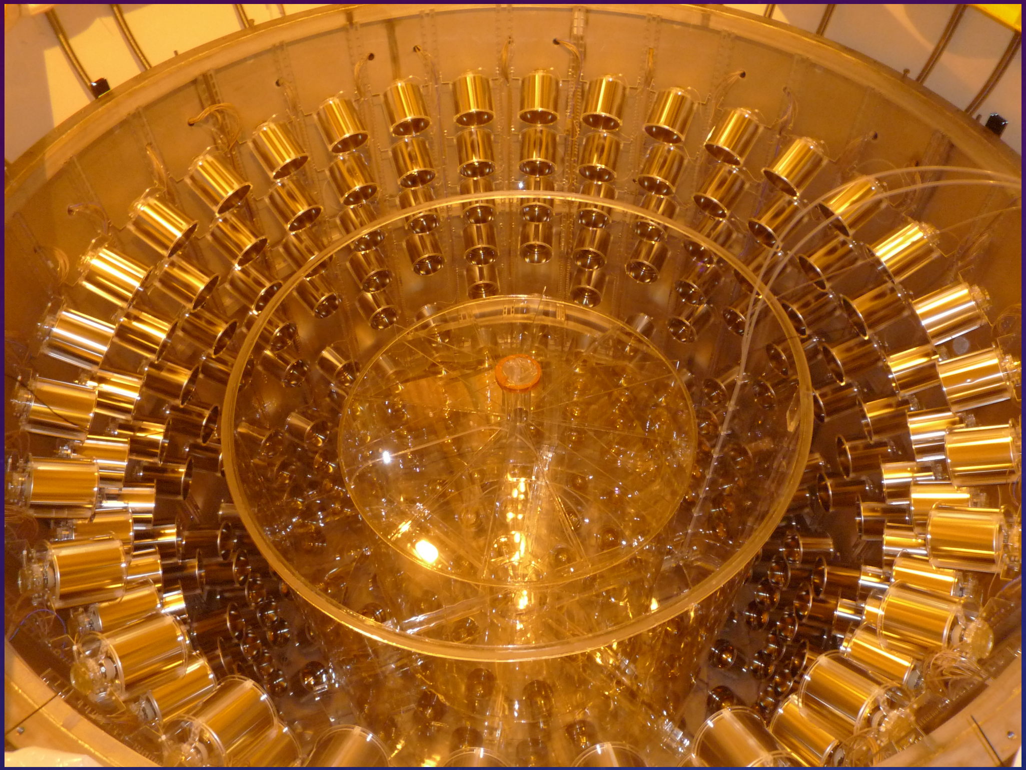

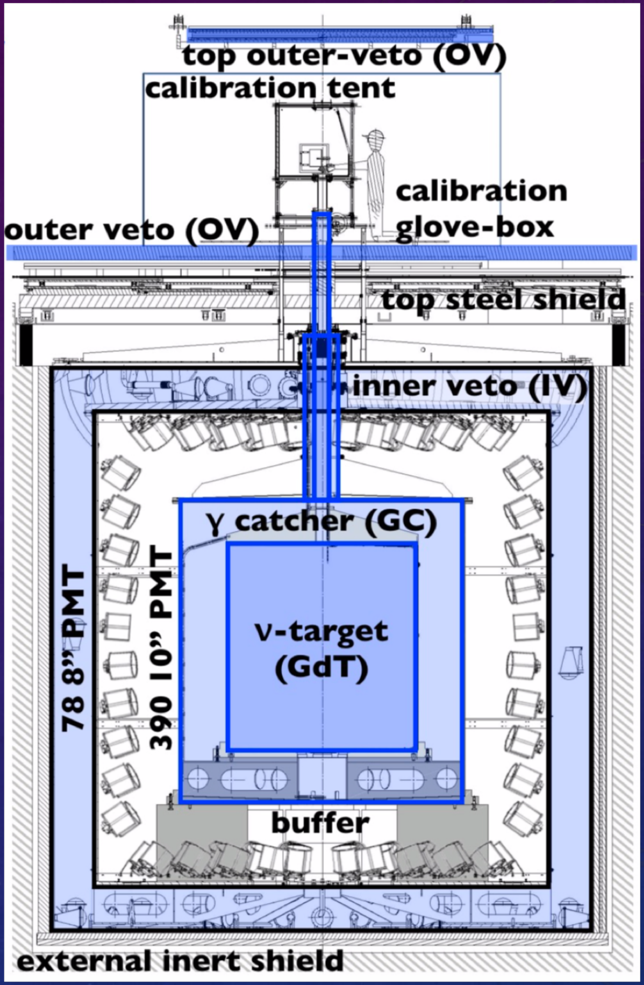


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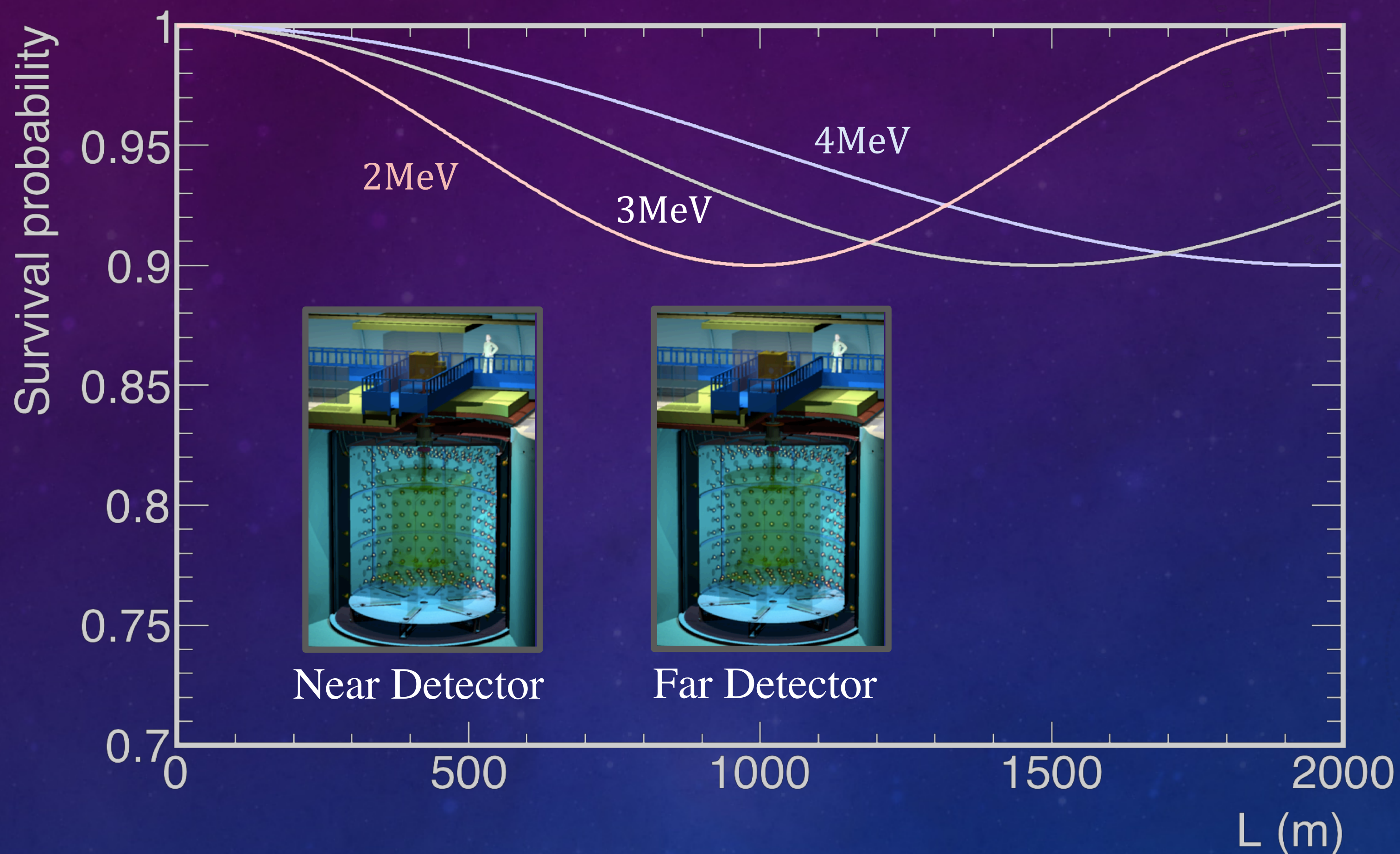
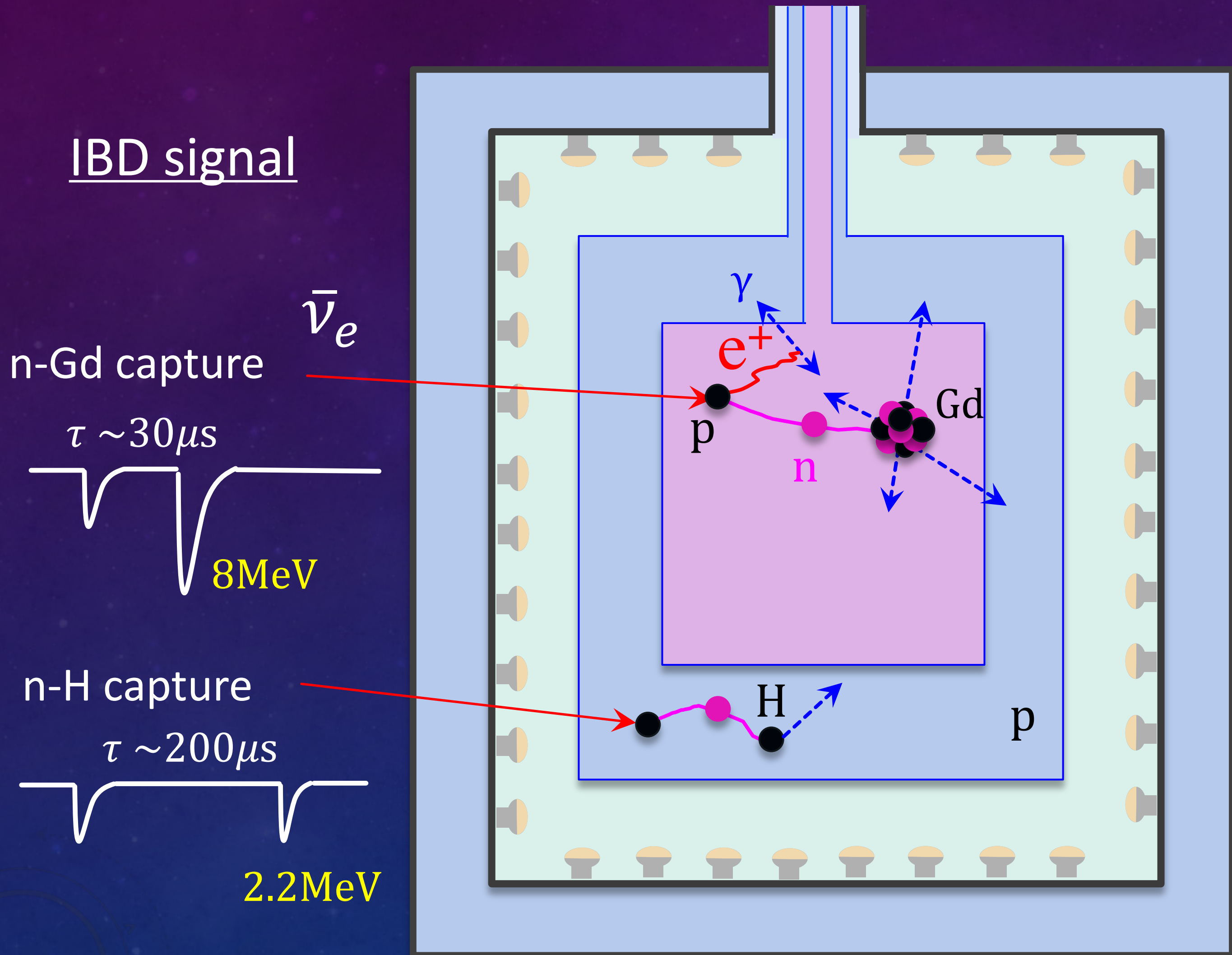
# EXPERIMENTAL SETUP WITH MULTI-DETECTORS




- Place two or more almost-identical detectors at different baselines
- Systematic uncertainties on reactor flux prediction and detector response are largely cancelled in comparison

# SIGNAL & BACKGROUND

IBD signal

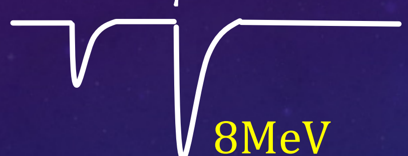


# SIGNAL & BACKGROUND

## IBD signal

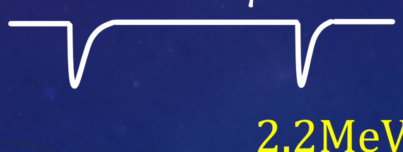
n-Gd capture

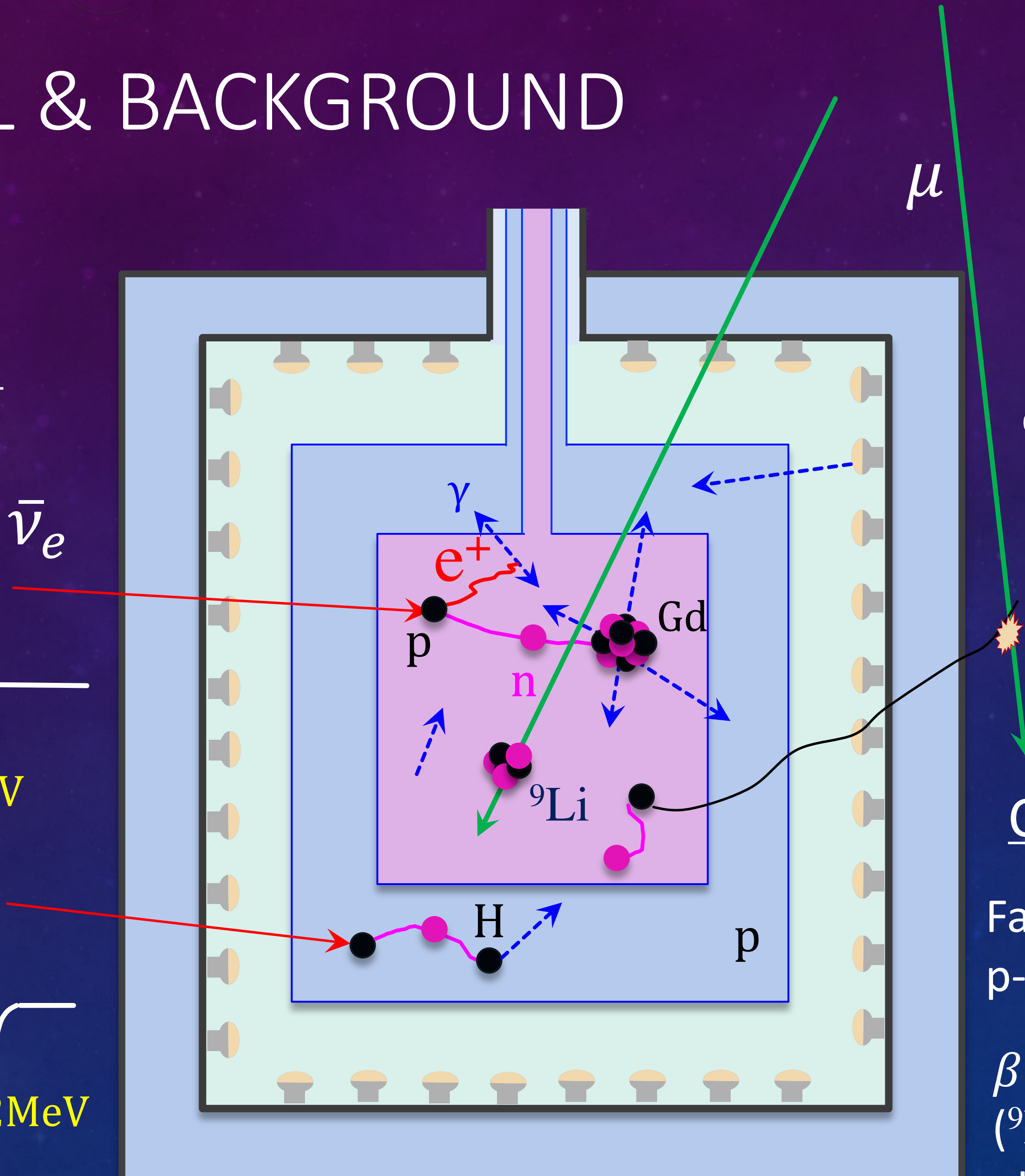
$\tau \sim 30\mu s$




n-H capture

$\tau \sim 200\mu s$




## Accidental BG

Random coincidence of two signals

$\gamma + \gamma$

$\gamma$ + n-capture

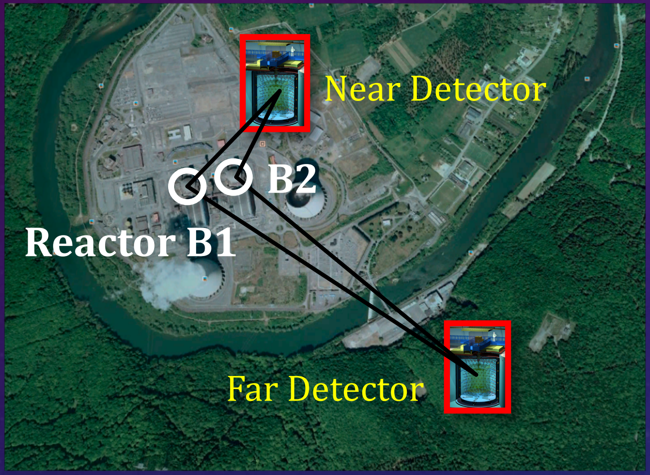
## Cosmogenic BG

Fast neutron:
p-recoil + n-capture

$\beta + n$ emitter
($^9$Li, $\tau = 257$ms):
electron + n-capture

# THREE REACTOR EXPERIMENTS IN THE WORLD

Double Chooz




Daya Bay


RENO


- $\theta_{13}$ is measured by reactor experiments with <1% systematic uncertainties
- Reactor $\theta_{13}$ is used as input to current and future neutrino experiments aiming for precise measurement of neutrino mixing including $\delta_{CP}$ and mass hierarchy
- Validation by multi-experiments with different systematics are important

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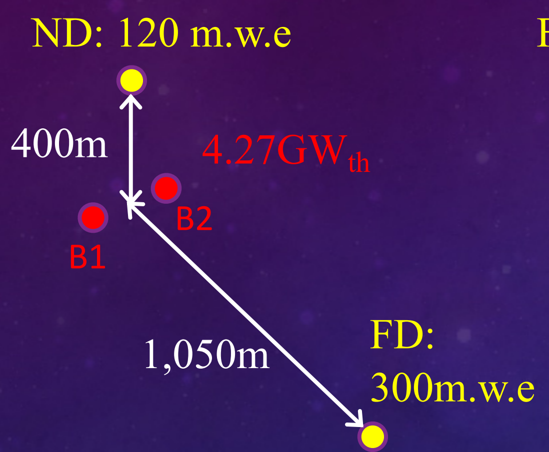
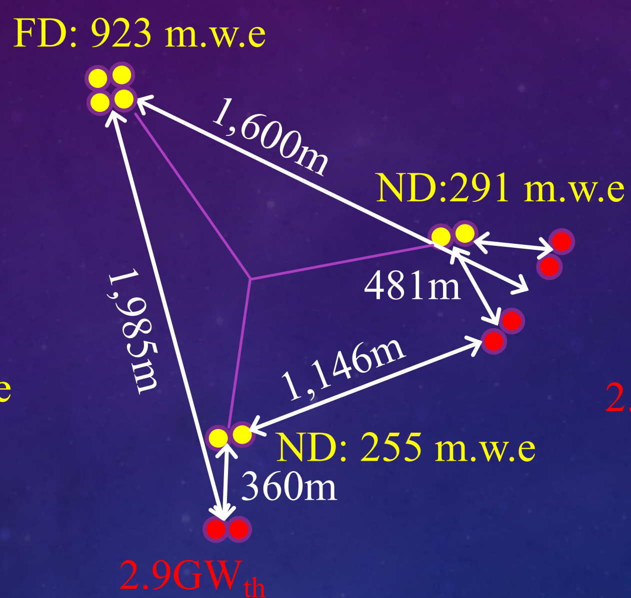



Nearly iso-flux condition:

$$\frac{L_{B1-ND}}{L_{B1-FD}} \approx \frac{L_{B2-ND}}{L_{B2-FD}}$$

## Daya Bay

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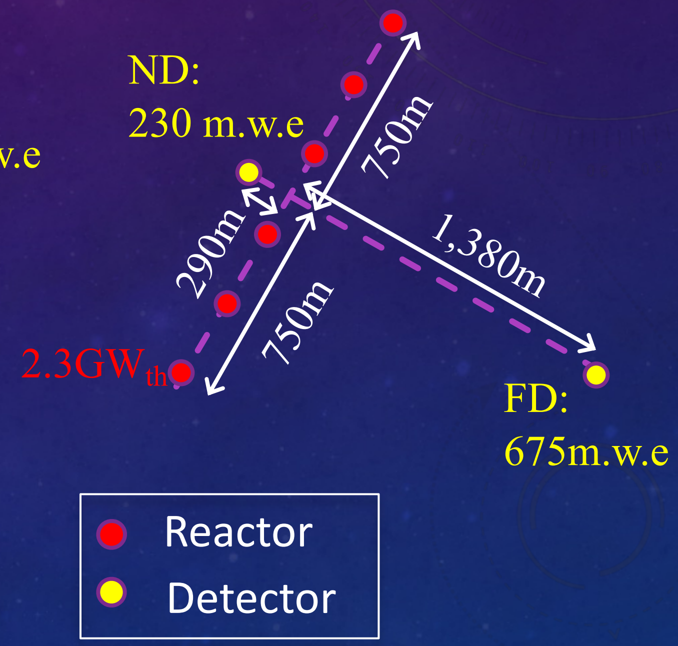


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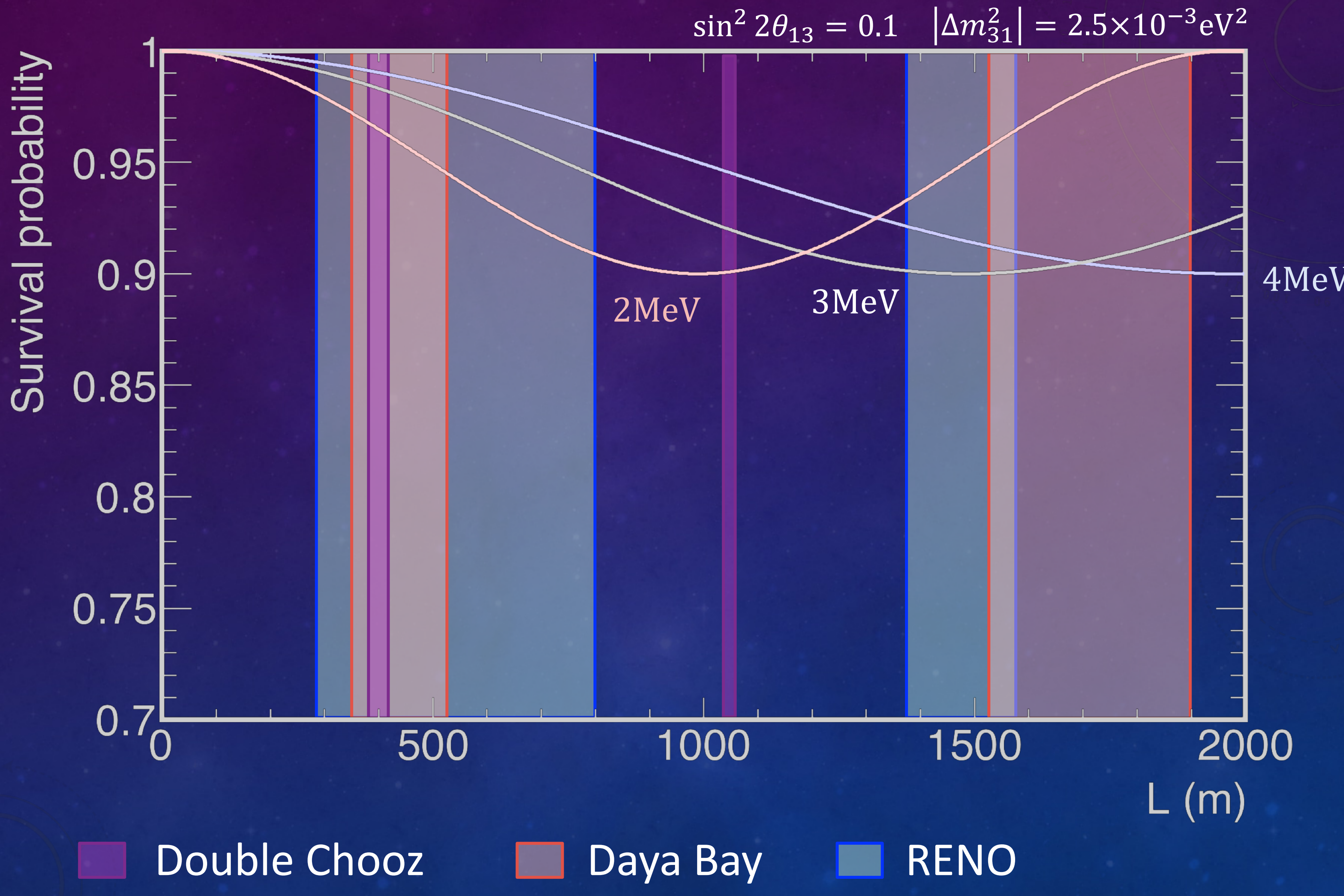

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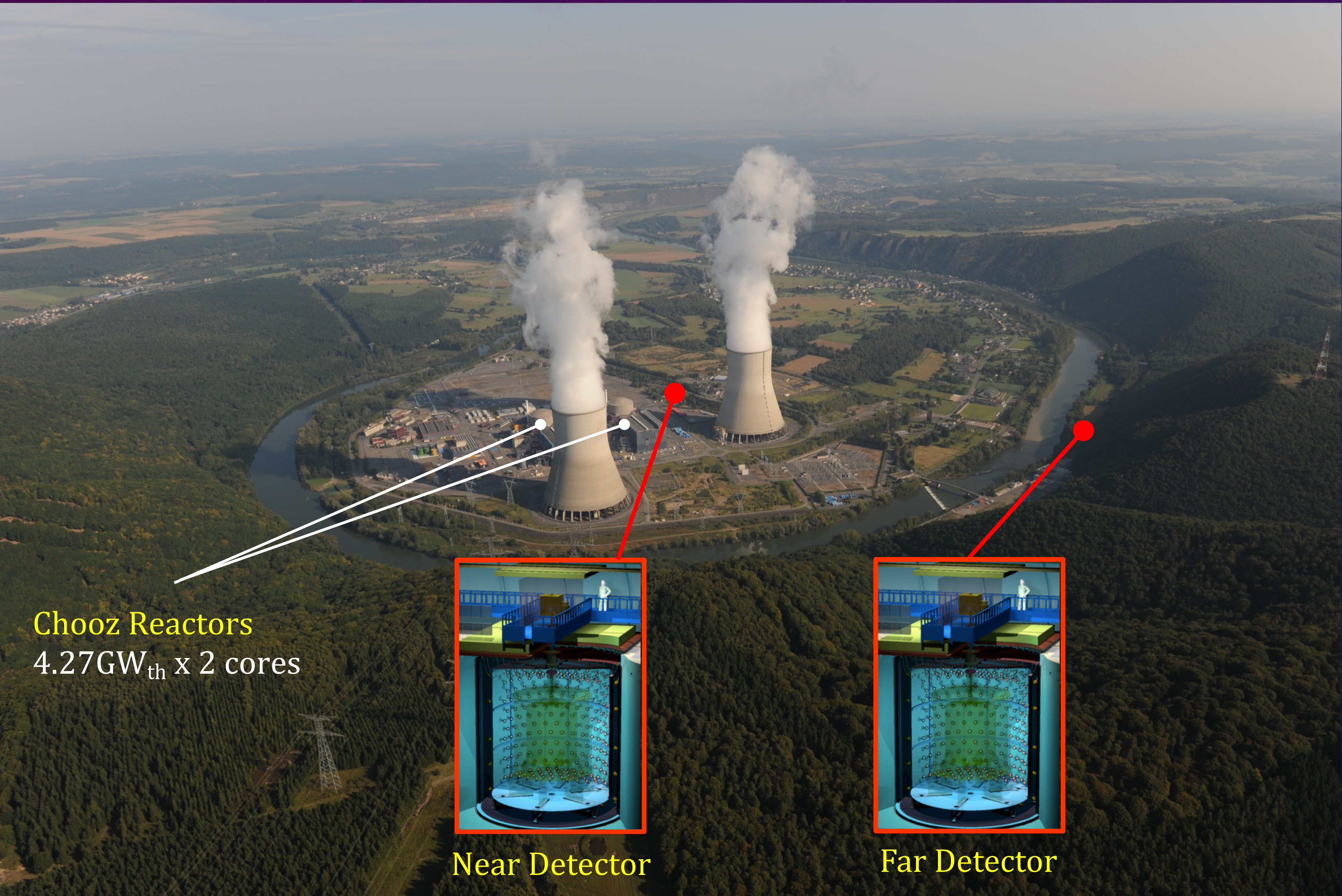
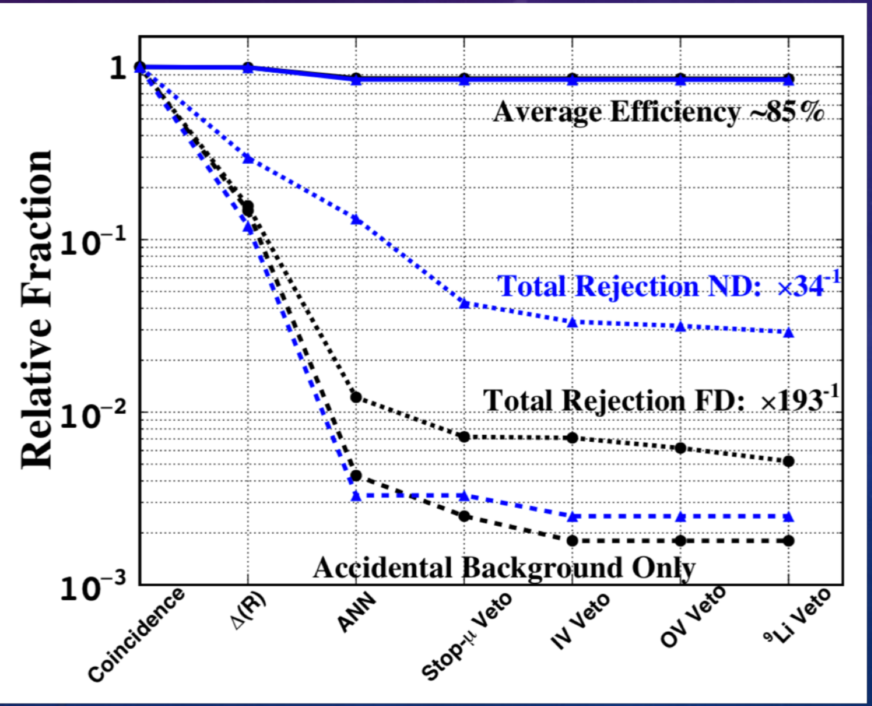
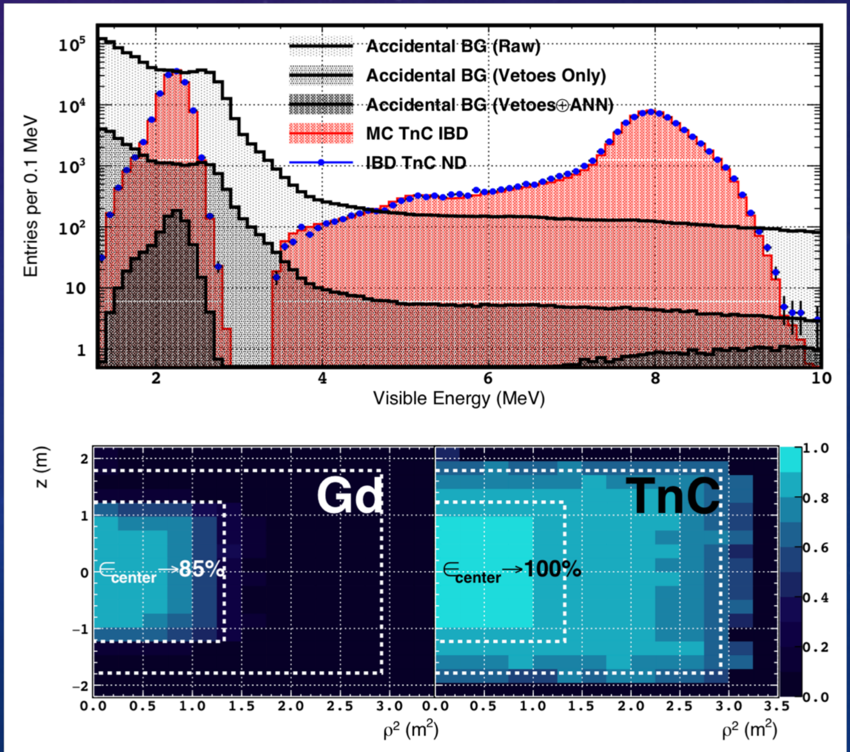


# Double Chooz

- Indication of non-zero $\theta_{13}$ in 2011 (94%CL) – first result since CHOOZ
- New method: total neutron capture detection (n-H + n-Gd + n-C)
  - Improve statistics by factor 2.5 with extended target mass
  - Realized by strong BG reduction with ANN and various vetoes

*arXiv:1901.09445*



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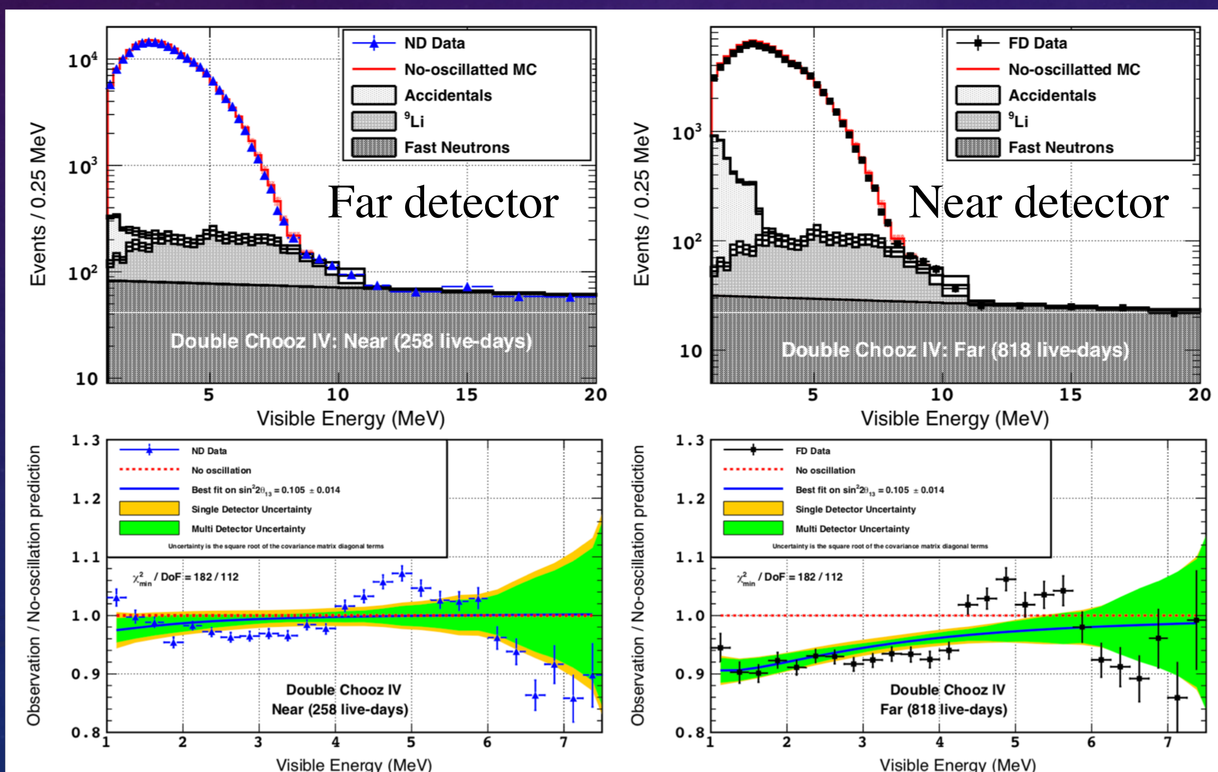
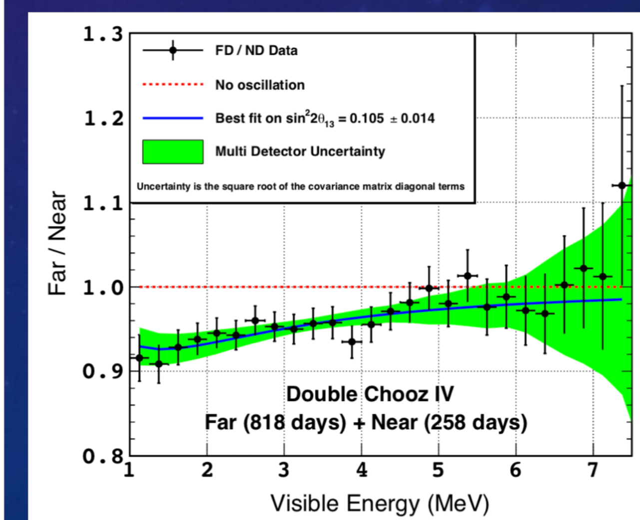


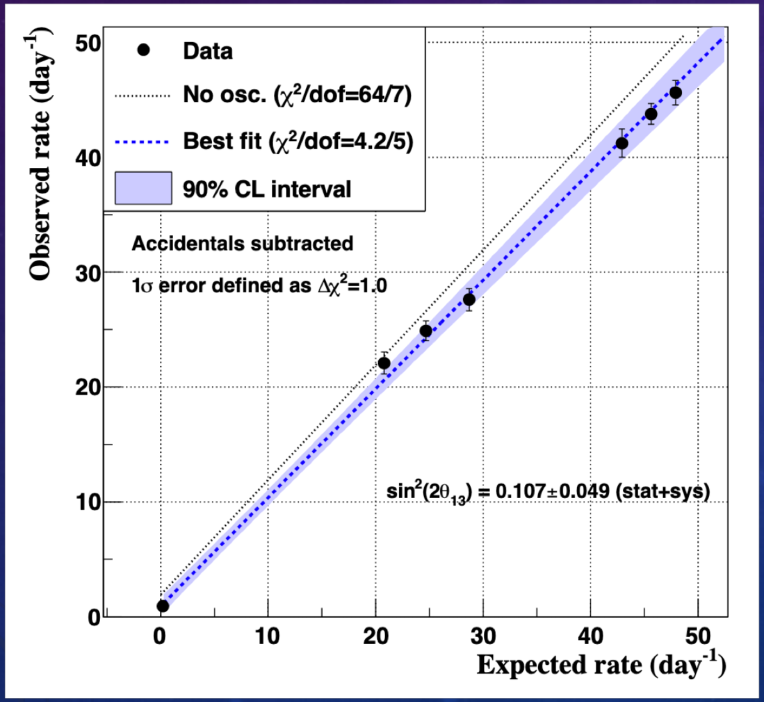

Far/Near ratio



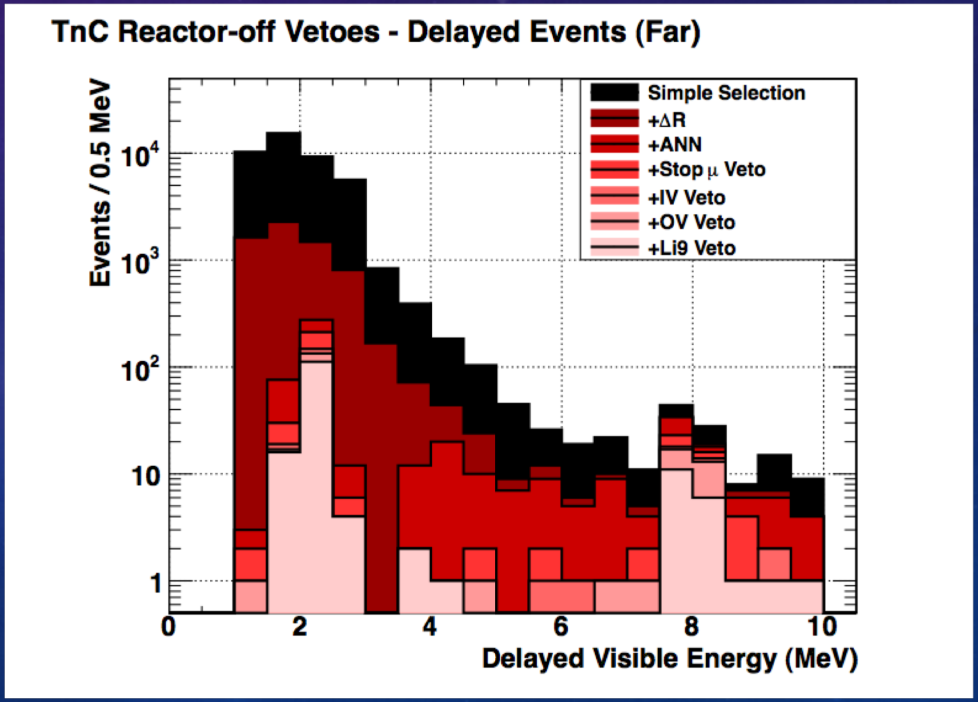

*arXiv:1901.09445*

# Double Chooz

- Simple experimental setup with two reactors
  - Flux uncertainty largely suppressed
  - Reactor rate modulation analysis
  - Direct measurement of background with reactor-OFF data




*Phys.Lett. B735 (2014) 51-56*

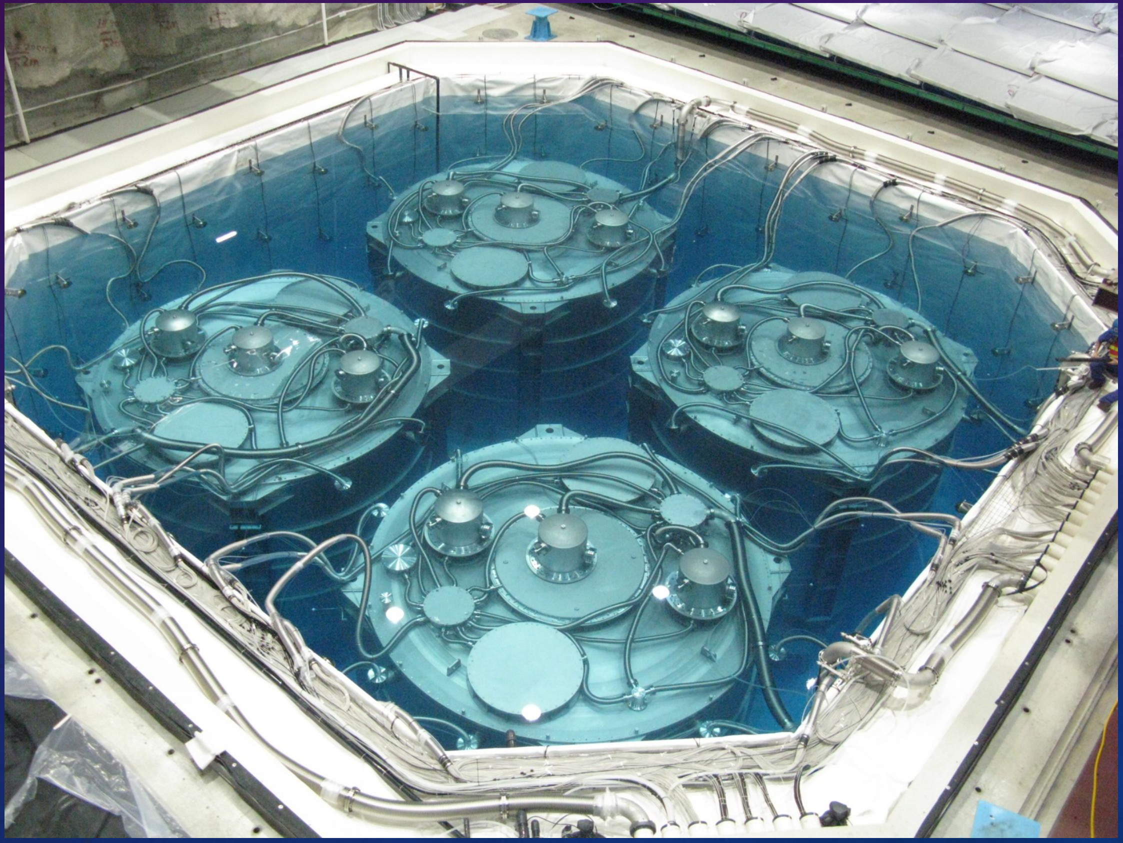


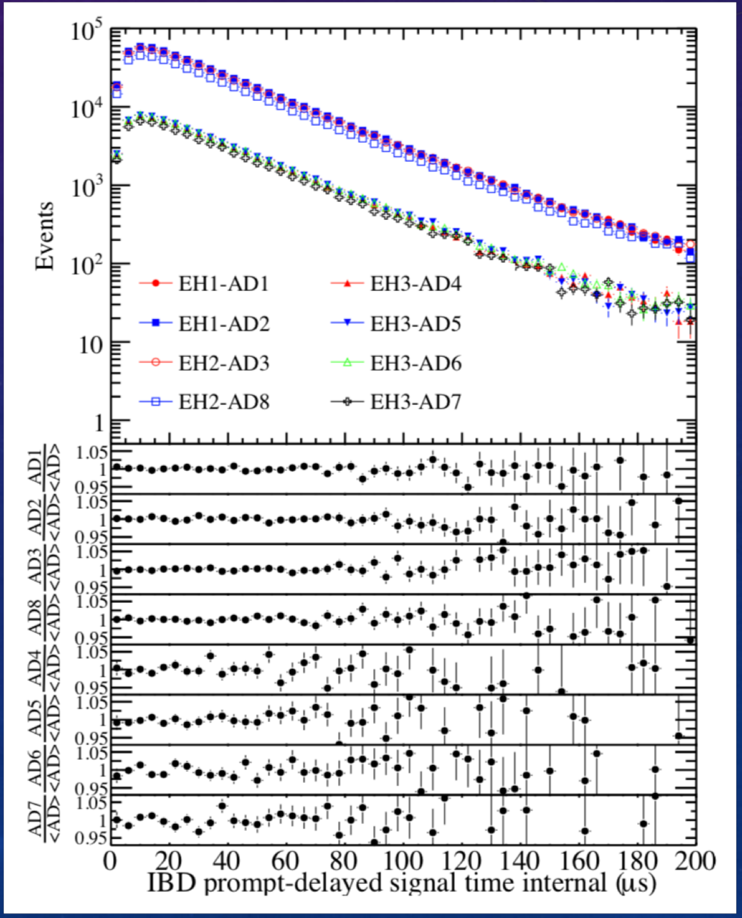

*C. Buck, Neutrino'18*

# Daya Bay

- Side-by-side calibration with multiple detectors at each site
- Detector response validated by automated calibration system

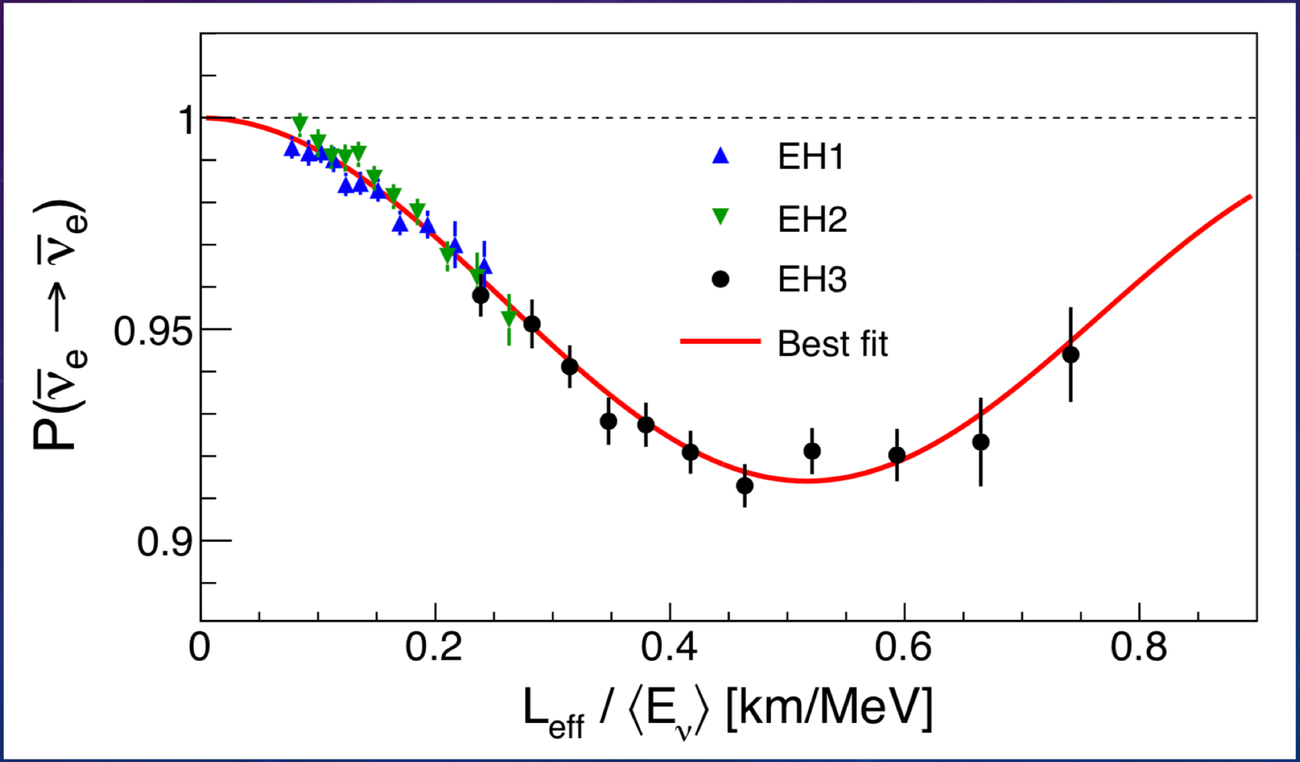
*Phys. Rev. D 95, 072006 (2017)*





# Daya Bay

- Reported $5\sigma$ observation of non-zero $\theta_{13}$ in 2012 and has been leading the precision measurement
- Three sites cover wide range of $L/E \rightarrow$ sensitive to $\Delta m^2_{ee}$
  - $\Delta m^2_{ee} \equiv \cos^2\theta_{12}\,\Delta m^2_{31} + \sin^2\theta_{12}\,\Delta m^2_{32}$ *S. Parke, Phys. Rev. D 93, 053008 (2016)*

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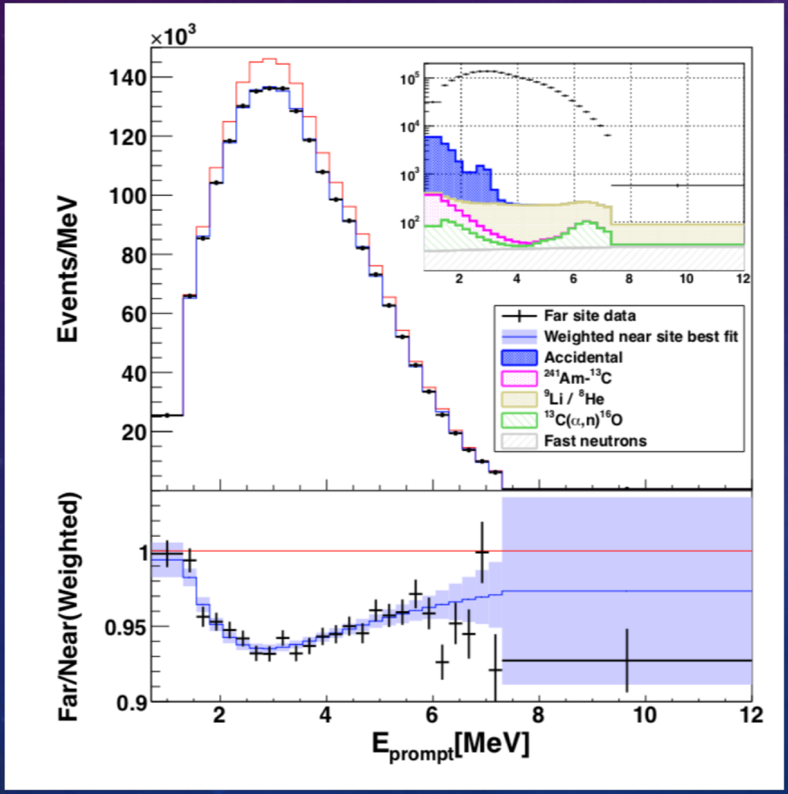
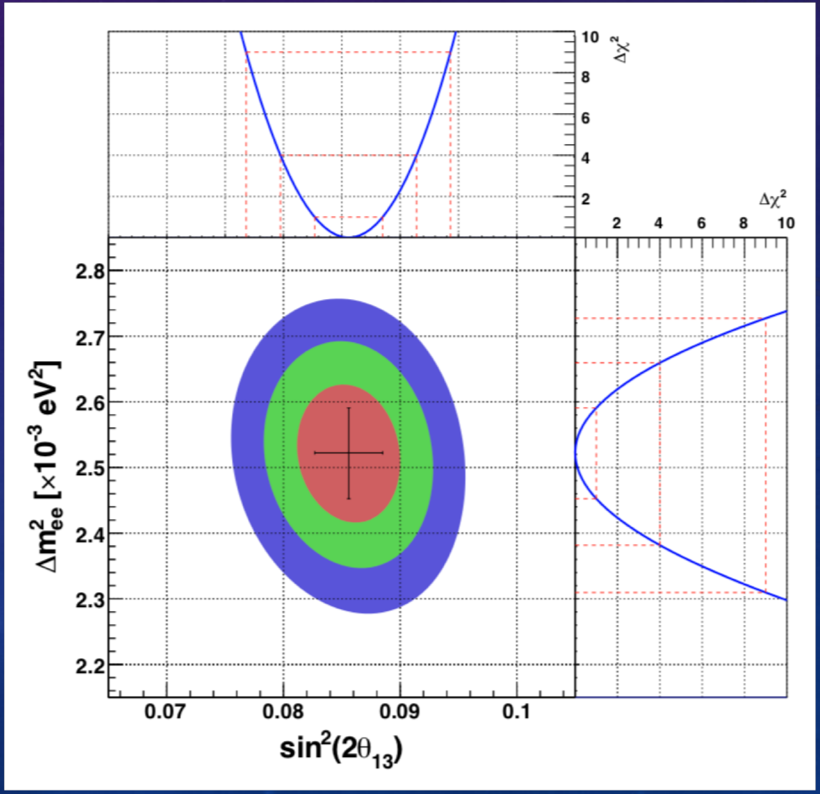
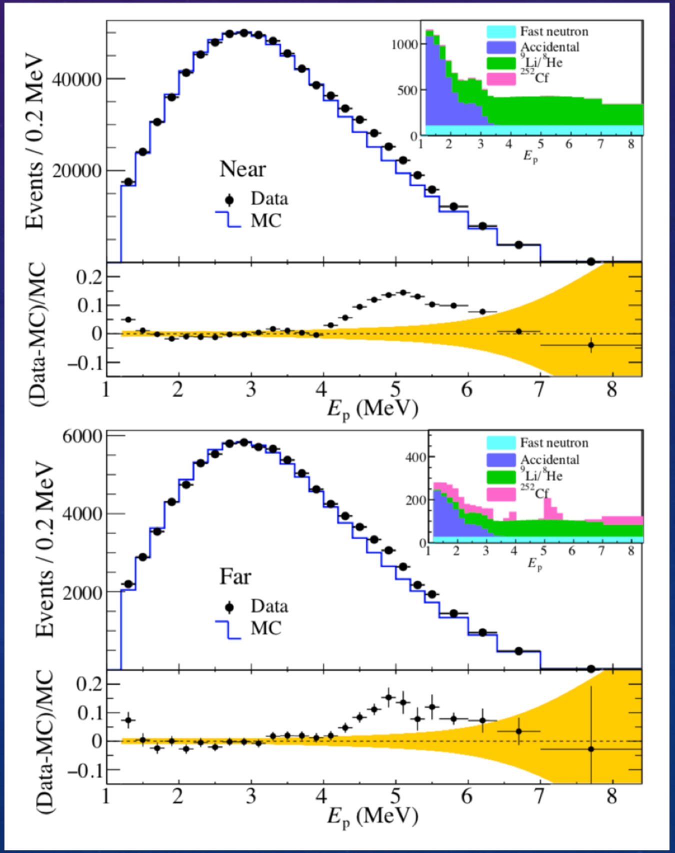



*Phys. Rev. Lett. 121, 241805 (2018)*

# RENO

- Confirmed non-zero $\theta_{13}$ soon after Daya Bay in 2012
- Measured $\Delta m^2_{ee}$ consistent with Daya Bay
- Recently reported fuel-composition studies (later slides)



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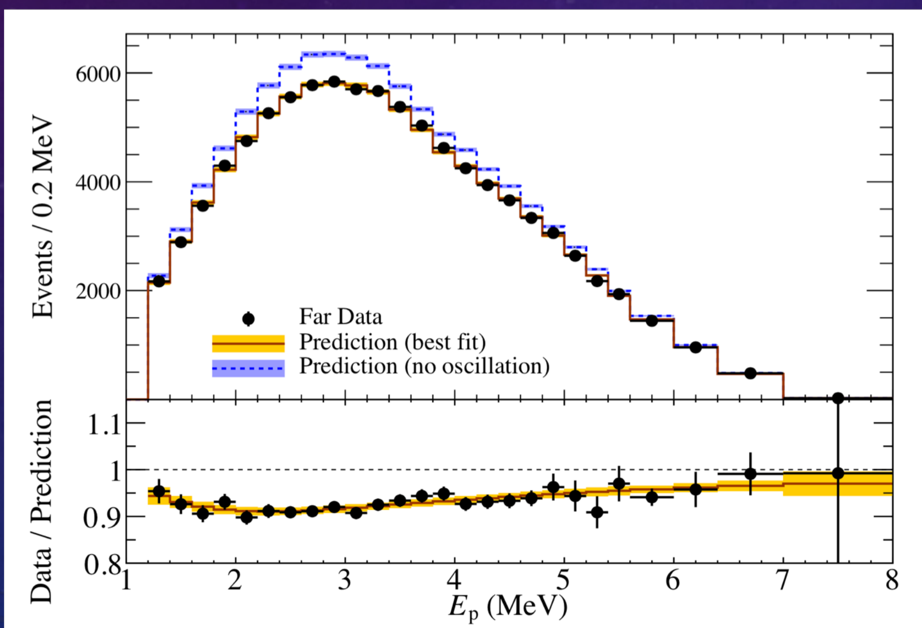
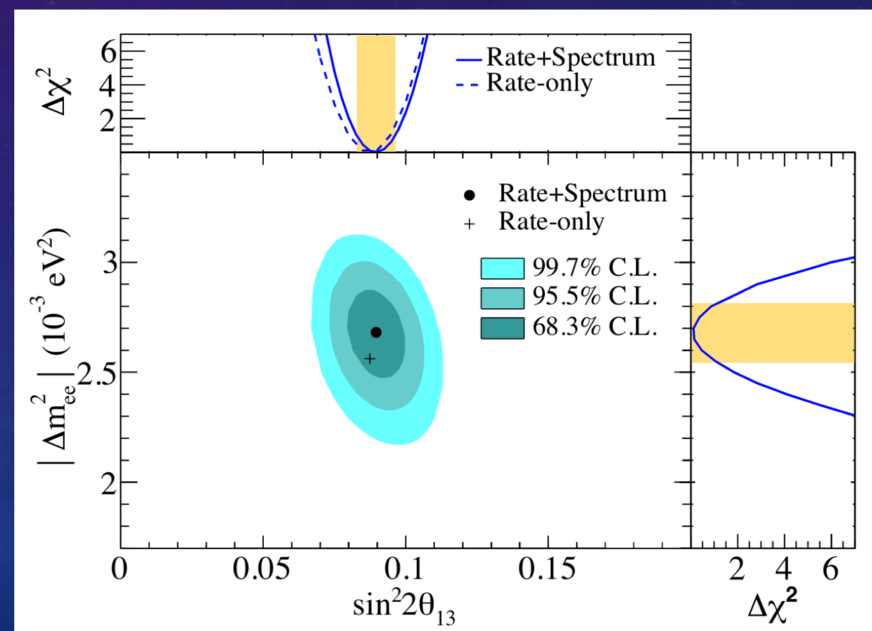


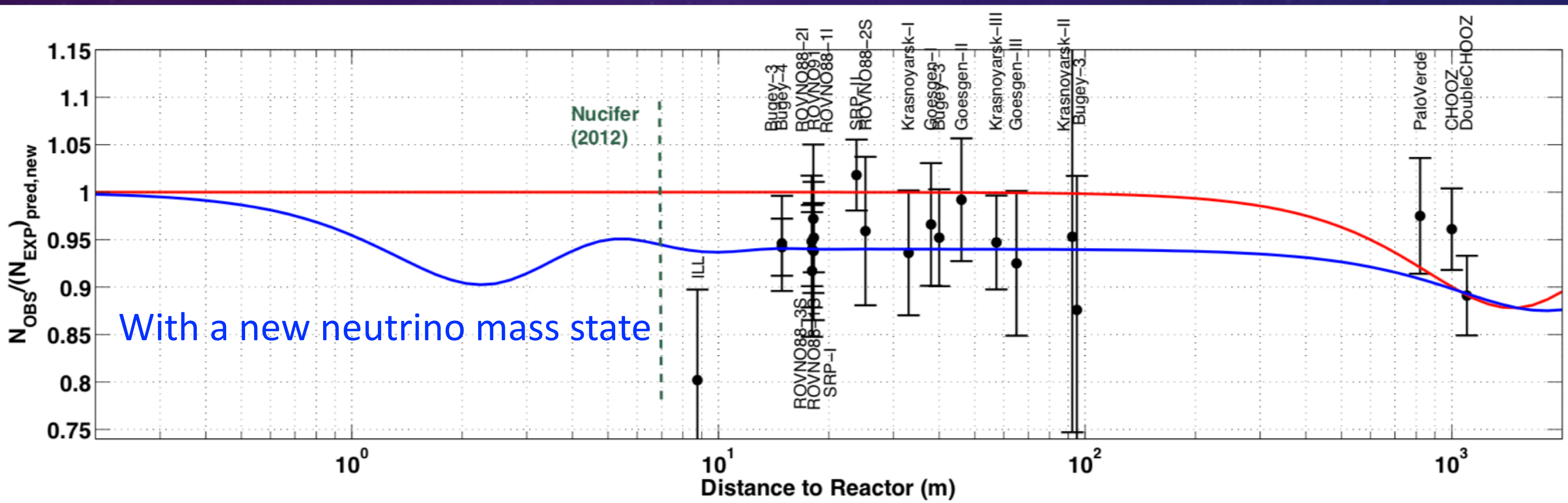




Prediction based on ND measurement

# REACTOR MODEL: RATE

- Several past experiments reported rate observation lower than prediction (Huber-Mueller model) by ~6% → reactor anomaly

*Light Sterile Neutrinos: A White Paper, arXiv:1204.5379*



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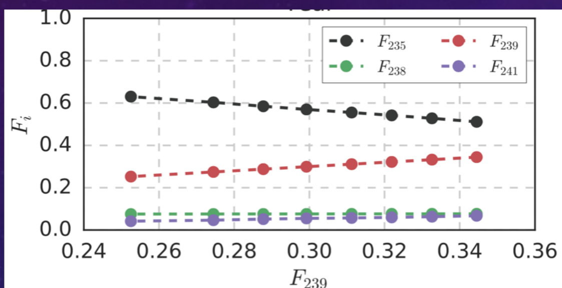
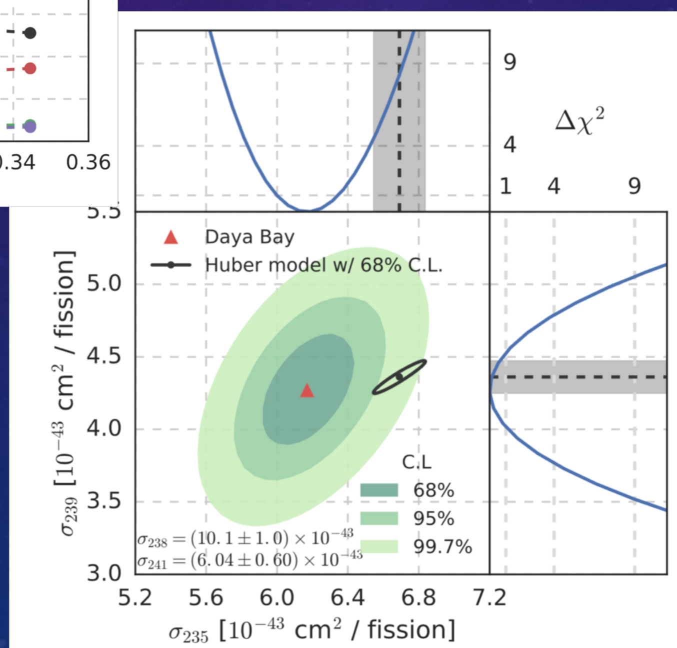
- Data taken with different fuel-compositions indicate the deficit is in neutrinos from $^{235}$U



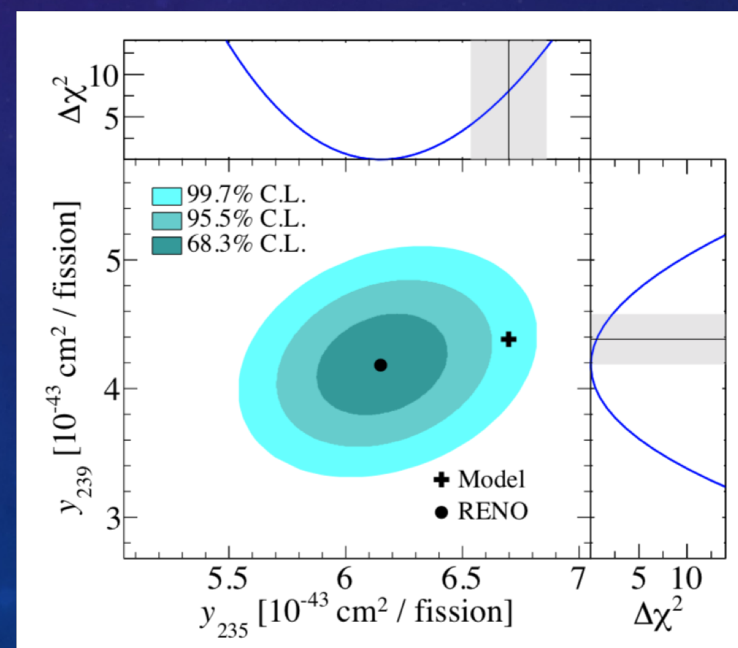

Daya Bay

*PRL118, 251801 (2017)*



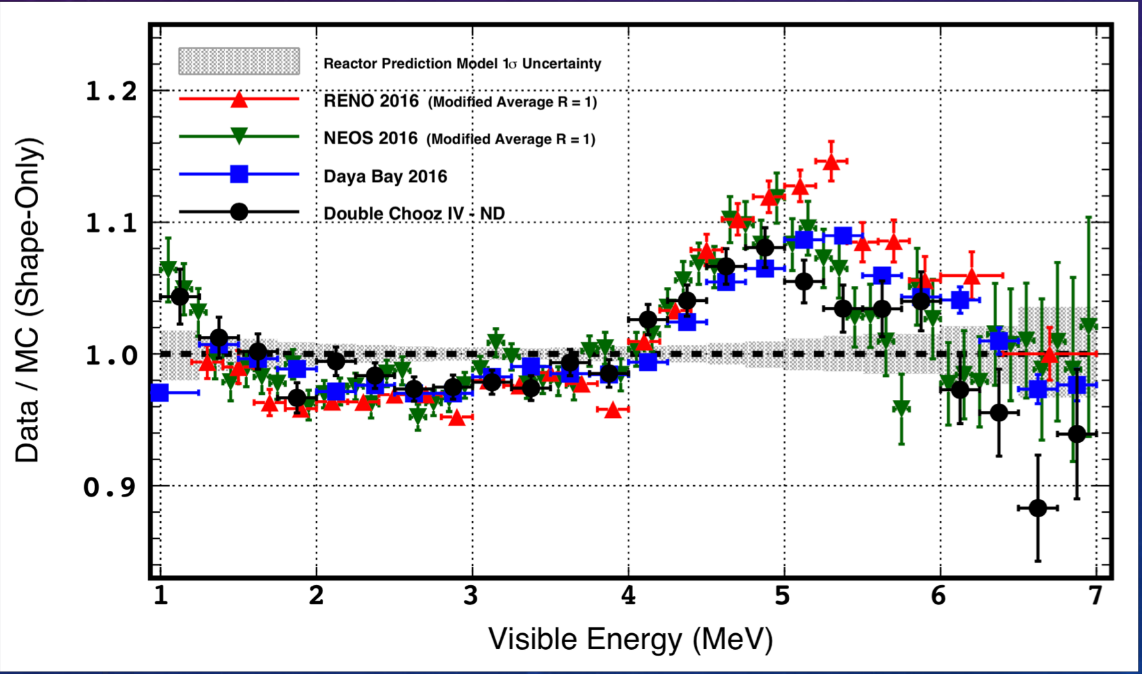

RENO

*arXiv:1806.00574 (2018)*



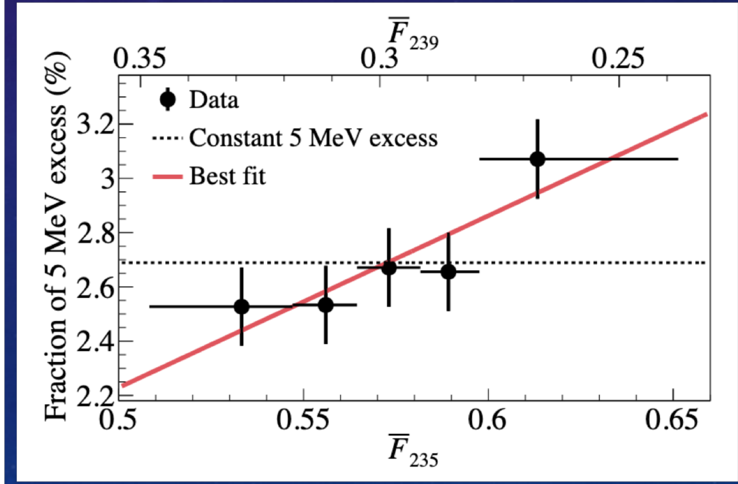
# REACTOR MODEL: SPECTRUM

- Significant distortion was observed in reactor neutrino spectrum
- Three experiments with different background compositions reported similar distortion → unlikely due to background
- The cause is not yet understood
- Distortion consistent in ND and FD → cancelled in $\theta_{13}$ measurements




*DC, arXiv:1901.09445*

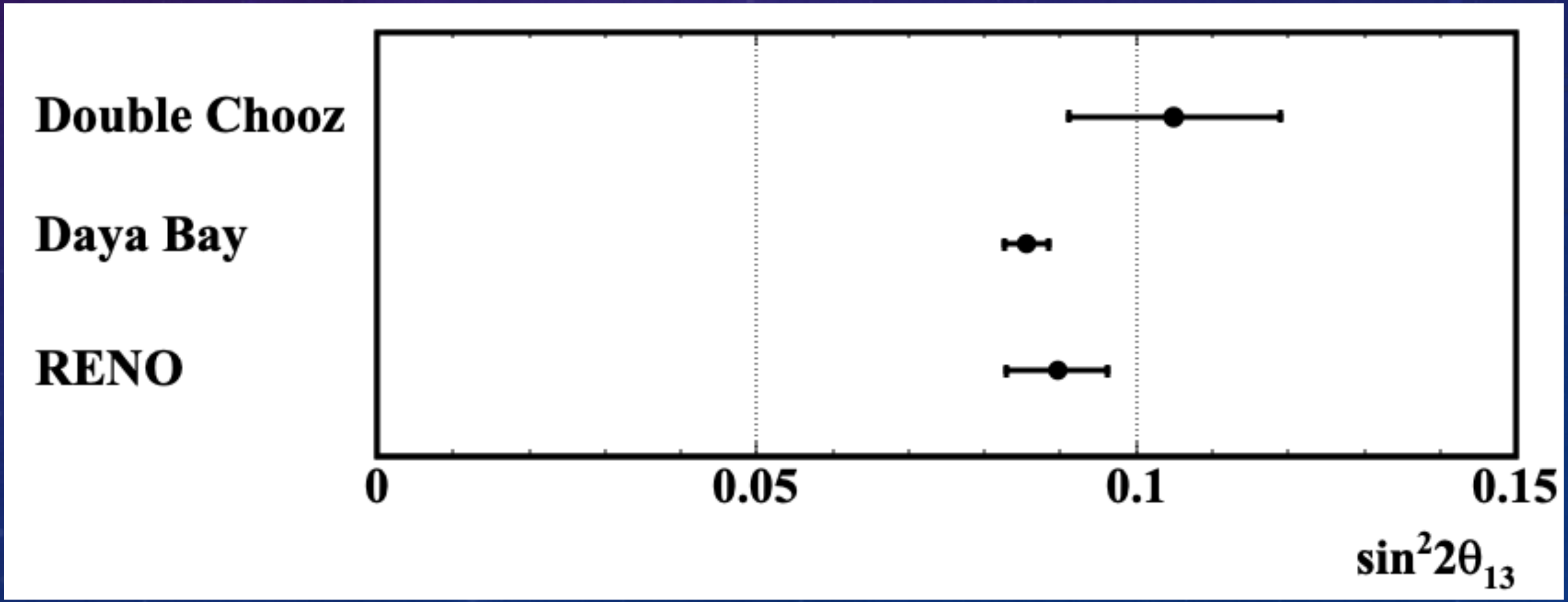
*RENO, arXiv:1806.00574*




RENO reported indication of correlation with $^{235}$U fraction

# $\theta_{13}$ measurements from reactor experiments

- From latest results
  - Double Chooz $\sin^2 2\theta_{13} = 0.105 \pm 0.014$ *arXiv:1901.09445*
  - Daya Bay $\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$ *PRL121, 241805 (2018)*
  - RENO $\sin^2 2\theta_{13} = 0.0896 \pm 0.0067$ *PRL121, 201801(2018)*



# SUMMARY AND PROSPECTS

- Three reactor experiments measured $\theta_{13}$ with various improvements with respect to CHOOZ (detector, scintillator and multi-detectors method)
  - The value of $\theta_{13}$ was found close to the edge of CHOOZ limit
  - Double Chooz reported indication of non-zero $\theta_{13}$ in 2011.
  - Daya Bay observed $\theta_{13}$ with $5\sigma$ significance in 2012 $\rightarrow$ **$\theta_{13}$ established**.
  - RENO soon confirmed $\theta_{13}$ in 2012.
  - **Reactor experiments achieved precise measurement with the systematic uncertainties controlled at per-mil level.**
  - Three experiments reported similar distortion in reactor spectrum incompatible with the reactor flux model (source is as-yet-unknown)
- Now reactor $\theta_{13}$ measurements are approaching the final stage
  - Reactor $\theta_{13}$ will be used for decades as input to future experiments aiming for revealing whole picture of neutrino mixing.
  - Stay tuned for the $\theta_{13}$ outputs from reactor experiments.